

Materials Technology Slurry preparation

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7. INTRODUCTION

Slurry preparation has technically and economically an influence in the so-called "Wet Process" and "Semi-wet" Process of clinker burning.

Economical Considerations

The "Holderbank" Group operates about 1/3 wet process of all plants world-wide (about 70 plants).

Subject of "Slurry preparation" therefore, has an outstanding importance on the economical situation of the whole group.

It is anticipated that optimisation and automatic control of slurry properties will reduce the water content at a minimum of 5% slurry as a long time average. The reduction will be in the range of 5%, as a long-term.

A reduction of 5% slurry water content saves about 400 kJ/kg cli. For the production of 11 Mio t of clinker per year this translates into a total reduction of 150'000 t coal per year which means about 10 Mio US\$ saving potential per year for the whole group.

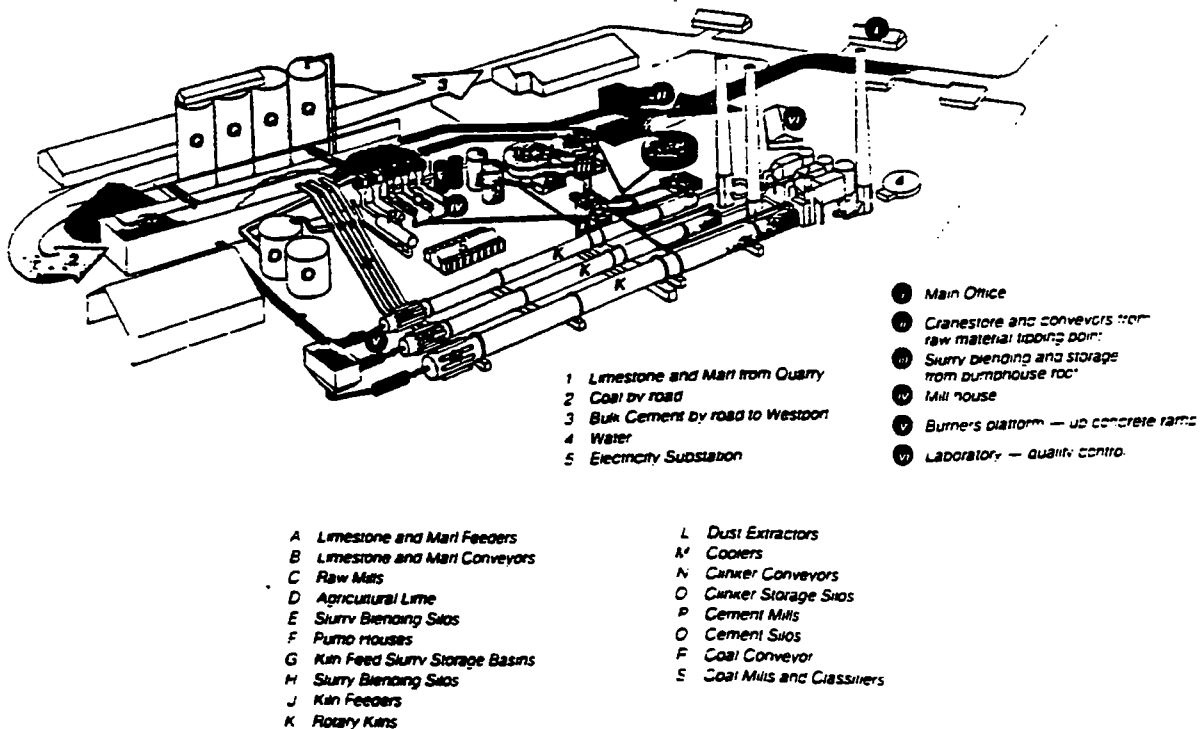
Wet Process

The wet process in the cement industry consists of finely grinding the raw materials, such as limestone, marl and clay with water in ball mills.

The fine slurry thus formed, which usually contains between 30 - 40% water, is then dried during the subsequent burning process in a long "wet" kiln in the so-called "Chain zone".

A typical plant layout (Milburn Cement, New Zealand) is shown in the following picture:

Fig. 1 Milburn Cement Plant.



In a wet-process kiln, a reduction in slurry moisture results in a reduction in heat use, and since both the amount of water vapour and the amount of combustion products are decreased, this also results in lower exhaust fan power use. The water content of the slurry also influences the demand on pumping energy.

As a result of price increase in the past years of various types of energy carriers such as oil and coal, great efforts are being made to use as little water as possible in the grinding of raw slurries.

A minimum amount of water must be added because the slurry is transported by pumps and must therefore, demonstrate a sufficient flowability.

Process features

The advantages of the wet and semi-wet process are:

- ◆ low investment (fixed costs)
- ◆ simple and stable process
- ◆ good compatibility with waste burning
- ◆ higher uniformity and quality of clinker
- ◆ simple operation and maintenance of the kiln.

The disadvantage is of course the higher thermal energy demand compared with the dry processes.

Slurry thinning

There are several possibilities for reducing slurry moisture while still maintaining pumpability. The most commonly used method is the addition of small amounts of viscosity-reducing agents. Other possibilities include carbonating the slurry with kiln exhaust gas, coarser grinding of the raw material, preheating the slurry and, if alternative raw material is available, substituting shale for clay.

Target values

Slurry preparation controls following items:

- ◆ Heat consumption due to water evaporation
- ◆ Consumption of mechanical energy due to
- ◆ evaporated steam and waste gas ventilation
- ◆ pumping the raw slurry, etc.
- ◆ Dimensioning of Piping/Filtration processes
- ◆ Evaluation of pumping system
- ◆ Mixing/Blending/Feeding
- ◆ Sedimentation/Flotation
- ◆ Corrosion
- ◆ Filtration (semi-wet process)

Several aspects to describe the slurry properties are known, some important ones are mentioned below:

- ◆ Water content
- ◆ Mineralogy
- ◆ Flow behaviour
- ◆ Granulometry
- ◆ Grindability
- ◆ Chemistry
- ◆ Pumpability
- ◆ Slump
- ◆ Specific grinding energy

8. RHEOLOGY

Rheology is the discipline describing the most important slurry property in a qualitative and quantitative manner.

There are off-line (laboratory) and on-line (process control) methods available.

Rheology describes the deformation of a body under the influence of stresses.

Ideal solids deform elastically. The energy of deformation is fully recovered when the stresses are removed.

Ideal fluids deform irreversibly - they flow. The energy of deformation is dissipated into the fluids in the form of heat, and it cannot be recovered just by releasing stresses.

Real bodies are neither ideal solids nor ideal fluids.

In their behaviour only a few liquids of technical or practical importance come close to ideal liquids. The majority of liquids show rheologically a behaviour that classifies them to a region between the liquids and the solids: they are in varying extents both elastic and viscous and may therefore, be named "viscoelastic".

The resistance of a fluid against any irreversible positional change of its volume elements is called viscosity. To maintain flow in a fluid, energy must be added continuously.

Viscometry deals specifically with the measurement of the flow behaviour of liquids including those showing a viscoelastic behaviour.

Definition Viscosity

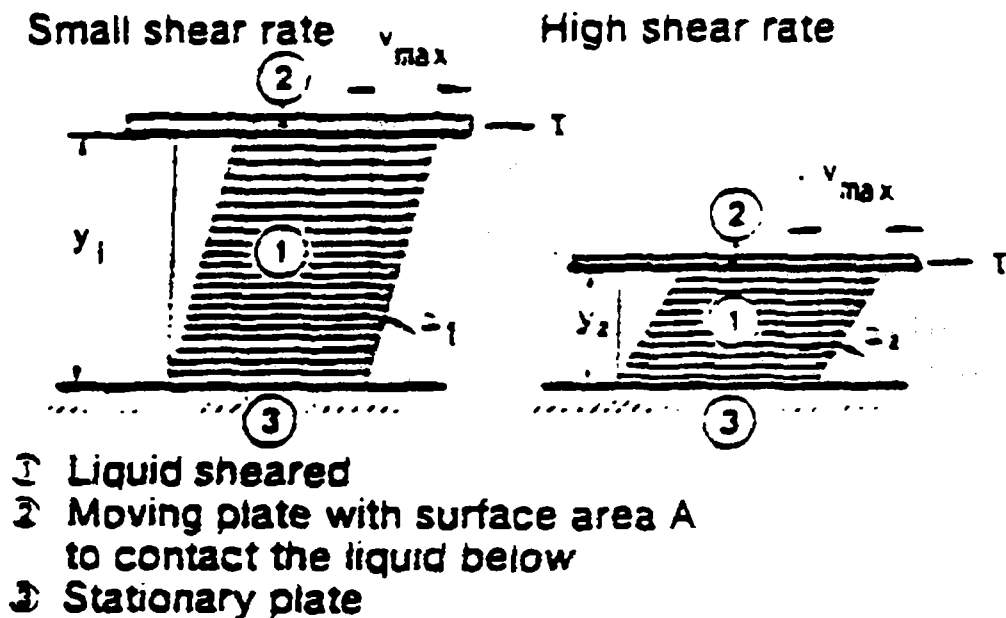
To measure the viscosity of liquids requires first the definition of the parameters which are involved in the flow. Then one has to find suitable test conditions which allow the measurement of flow properties objectively and reproducibly.

Isaac Newton was the first to find the basic law of viscosity describing the flow behaviour of an ideal liquid:

$\tau = \eta \times D$
$\eta = \text{Viscosity}$
$\tau = \text{Shear stress}$
$D = \text{Shear rate}$

The parallel plate model helps to define both shear stress and shear rate:

Fig. 2 Shear rates.



Shear stress

A force F applied to an area A being the interface between the upper plate and the liquid underneath leads to a flow in the liquid layer. The velocity of flow that can be maintained for a given force will be controlled by the internal resistance of the liquid, i.e. by its viscosity.

$$\tau = \frac{F(\text{force})}{A(\text{area})} = \frac{N}{m^2} = \text{Pa (Pascal)}$$

Shear rate

The shear stress τ causes the liquid to flow in a special pattern. A maximum flow speed V_{max} will be found at the upper boundary.

The speed drops across the gap size y down to $V_{min} = 0$ at the lower boundary contacting the stationary plate. Laminar flow means that infinitesimally thin liquid layers slide on top of each other, similar to cards in a deck-of-cards. One laminar layer is then displaced with

respect to the adjacent ones by a fraction of the total displacement encountered in the liquid between both plates.

In its general form the shear rate D is defined by a differential:

$$D = \frac{dv}{dx}$$

$$D = \frac{m/s}{m} = \frac{1}{s} [s^{-1}]$$

In case of a linear speed drop across the gap the differential in the equation above can be approximated by

$$D = \frac{V_{max}}{y} [S^{-1}]$$

Dynamic viscosity

Solving above equation for the dynamic viscosity gives:

$$\eta = \frac{\tau}{D} \quad \eta = \frac{N}{m^2} \times s = [Pa \times s]$$

The unit of dynamic viscosity is the "Pascal-second" [Pa x s].

Viscosity Parameters

The viscosity of a slurry is a function of various factors

Viscosity describing the physical property of a liquid to resist shear induced flow may depend on up to 5 independent parameters:

$$\eta = f(S, T, P, D, t)$$

(S) This most important parameter denotes the physical-chemical nature of a substance being the primary influence on viscosity (see also next pages "Material parameter").

(T) This parameter is linked to the temperature of the suspension. Viscosity is heavily influenced by changes of temperature.

(P) This parameter "pressure" is not experienced as often as the previous ones. Pressure compresses fluids and thus increase intermolecular re-sistance. Liquids are compressible under the influence of very high pressures - similar to gases but very much less. Increases of pressure tend to increase the viscosity.

(D) Parameter "shear rate D " is a decisive factor influencing the viscosity of many liquids. Increasing shear rates may decrease or increase the viscosity.

(t) Parameter "time" denotes the phenomenon that the viscosity of some sub-stances, usually dispersions, depends on the previous shear history, i.e. on the length of time the substance was subjected to continuous shear or was allowed to rest before being tested.

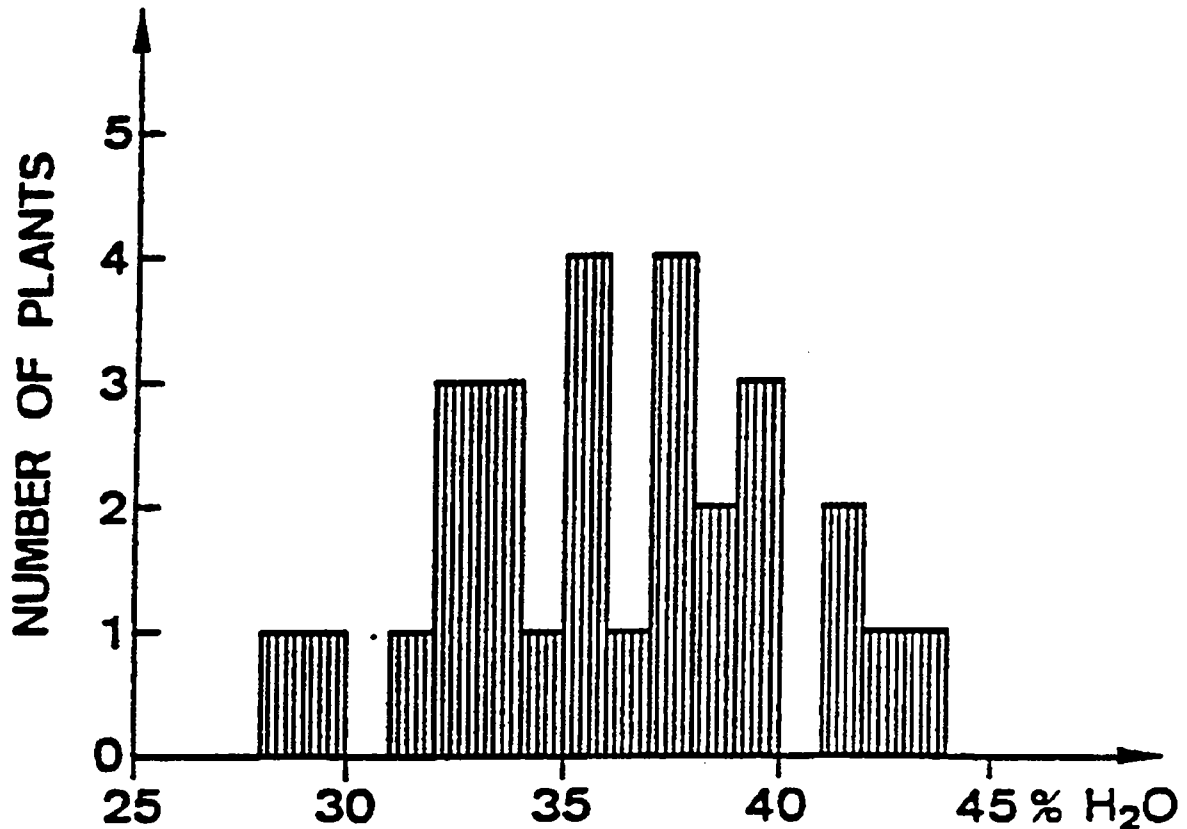
Material Parameter (S)

These parameter (S) is to be differentiated into the following sub-parameters:

A) Water Content

Approximately 30% of all "Holderbank"-Group plants (corresponding to approximately 35% of the total clinker production) are employing the wet-process for cement manufacture.

Fig. 3 Water content.



Generally it can be pointed out that the higher the water content, the lower the viscosity.

There are little restrictions with respect to the quality of the utilised water, i.e. water of many origin/source and quality can be used, such as:

- ◆ tap water
- ◆ industrial water/industrial waste liquids
- ◆ sewage water
- ◆ slightly brackish water.

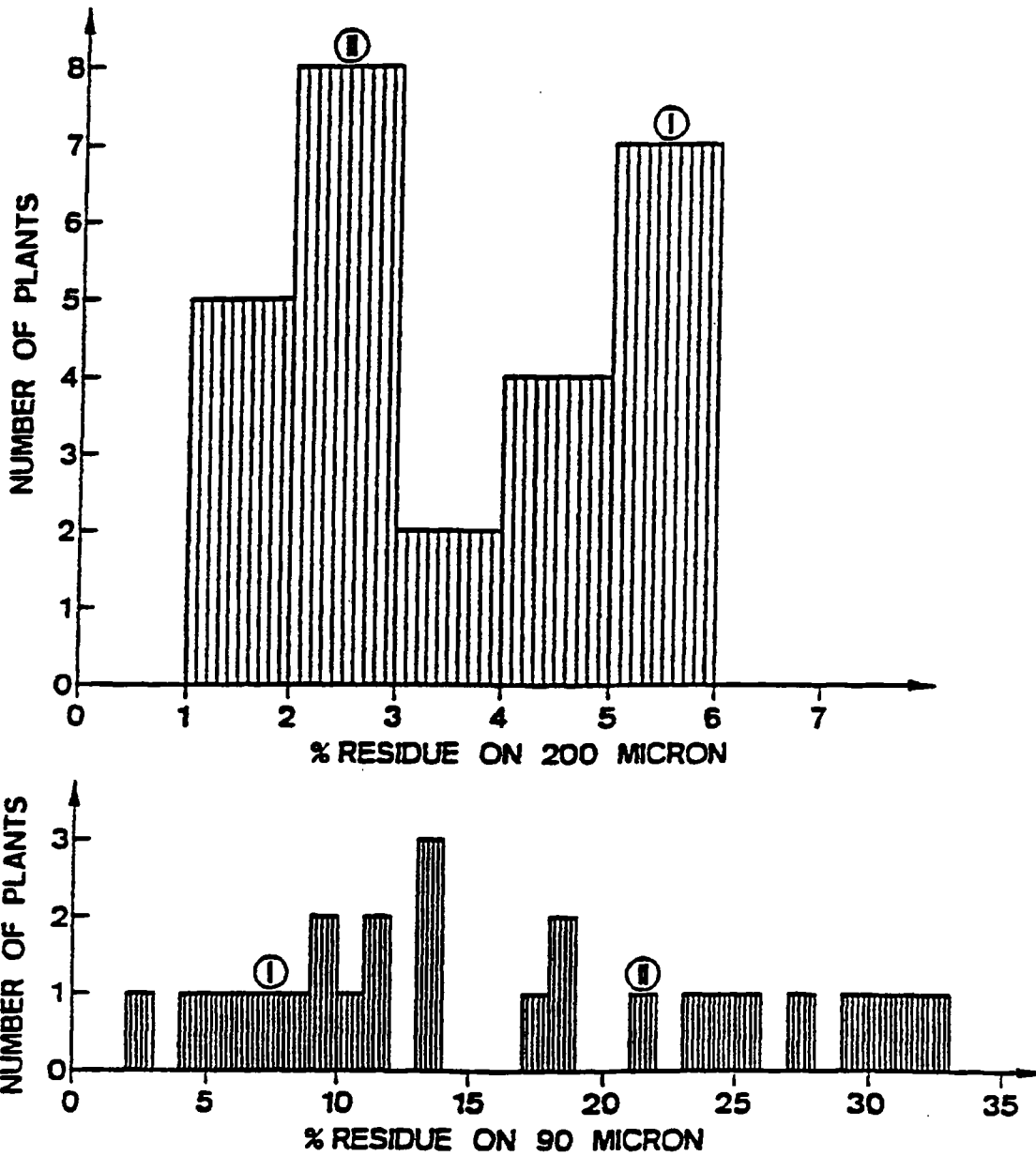
The only quality aspects which have to be controlled are:

- ◆ content of corrosive elements (C1, 0)
- ◆ contents of harmful or poisonous elements with regard to process, product and waste gases (C1, F, B, organic substances, etc.)
- ◆ content of smelling compounds in the waste water, etc.

B) Slurry Fineness

The fineness of slurry fluctuates in a wide range as demonstrated in the following diagram:

Fig. 4 Slurry Fineness.



The coarser the slurry fineness, the lower the viscosity.

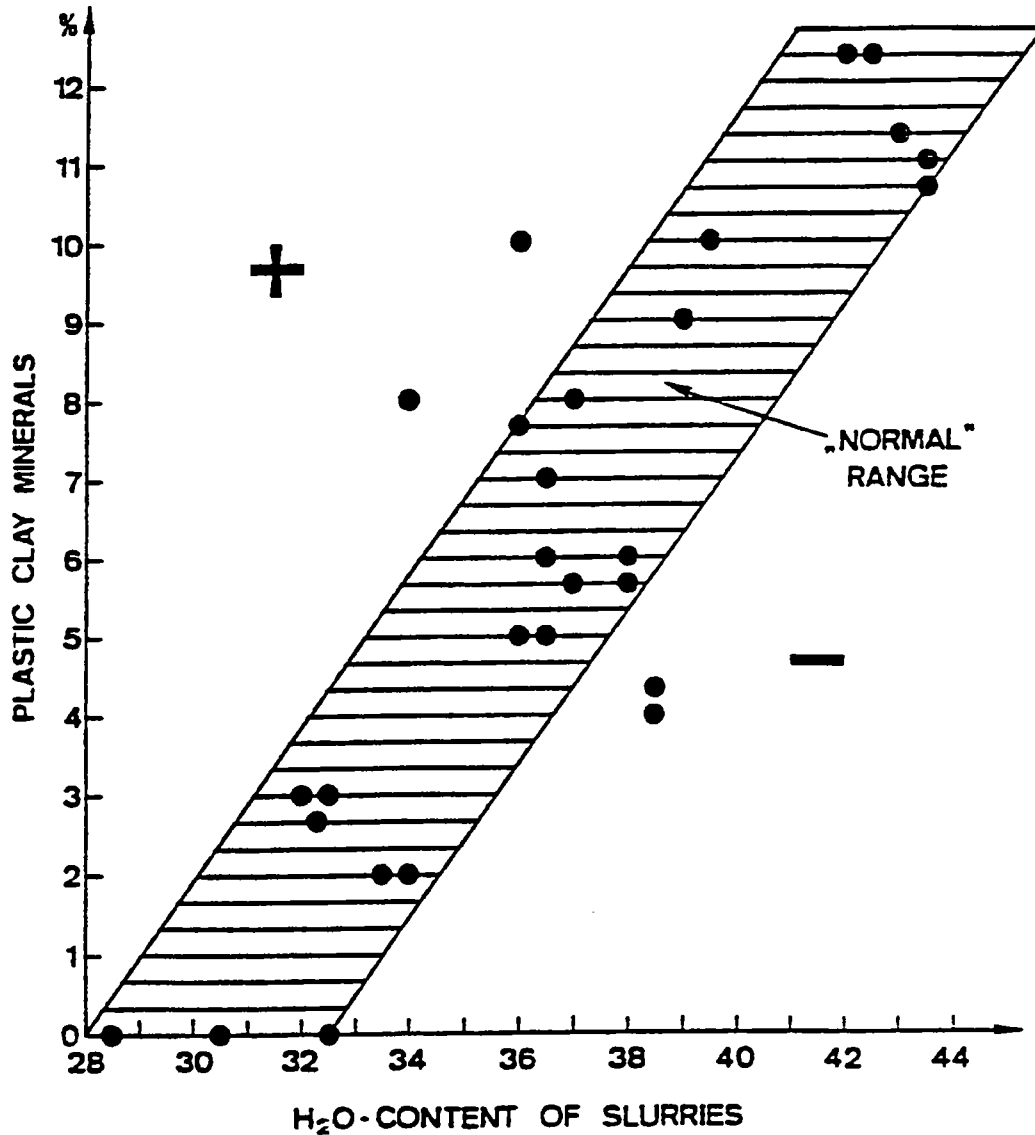
On the average, cement raw slurries have the following fineness characteristics:

mesh sieve	Micron	Wet Process	Dry Process
R 900	200	1 - 6%	0.5 - 2%
R 4900	90	5 - 30%	5 - 25%

C) Water content and Plastic clay

The relationship between slurry water-content and quantity of plastic clay minerals of some 25 cement plants, is displayed in the following figure which indicates the inter-dependence of these two parameters.

Fig. 5 Water content and Plastic clay.



The replacement of clay minerals, for instance with fly ash of thermal power plants, can reduce the water content significant by increased slurry flowability.

Other factors such as degree of fineness and grain size distribution of the raw mix, etc., also influence the slurry water-content, but the plastic clay mineral-content seems to be predominant.

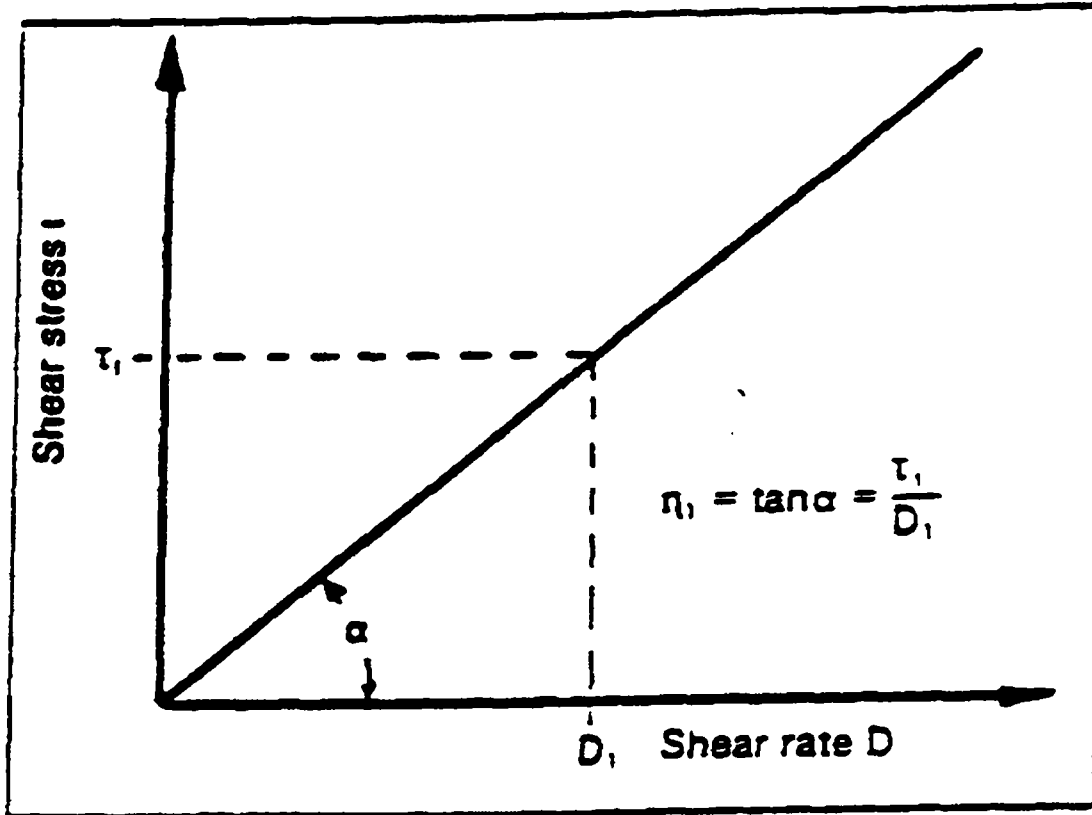
Viscosity Diagrams

Flow Curve

The correlation between shear stress and shear rate defining the flow behaviour of a liquid is graphically displayed in a diagram of τ on the ordinate and D on the abscissa. This diagram is called the "Flow Curve".

The most simple type of a flow curve is shown below. The viscosity is assumed to be constant and independent of D .

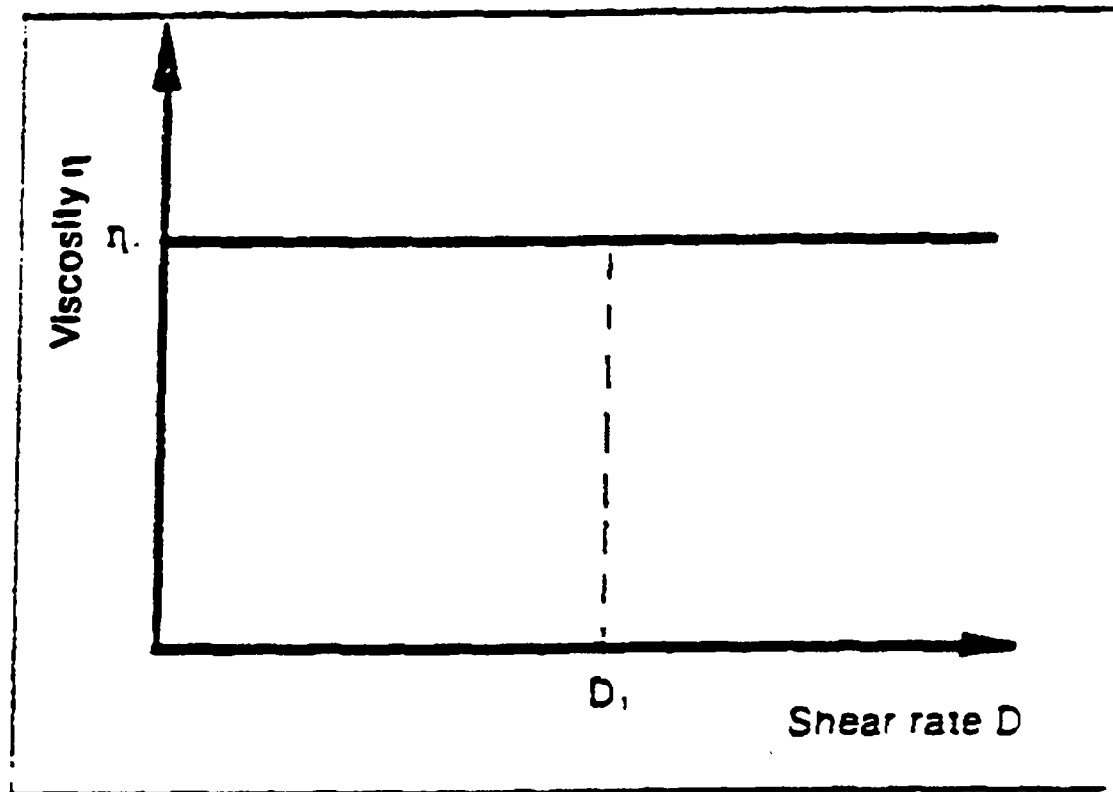
Fig. 6 Flow Curve.



Viscosity Curve

Another diagram is very common: η is plotted versus D . This diagram is called the "Viscosity Curve":

Fig. 7 Viscosity Curve.



Viscosity measurements lead always first to the flow curve. Its results can then be rearranged mathematically to allow plotting the corresponding viscosity curve. The different types of flow curves have their counterparts in types of viscosity curves.

8.1 Types of viscosity

Newtonian liquids

Newton assumed that the graphical equivalent of his equation for an ideal liquid would be a straight line starting at the origin of the flow curve and would climb with a slope of an angle α . Any point on this line defined pairs of values for τ and D . Dividing one by the other gives a value of n . This value can also be defined as the tangent of the angle α .

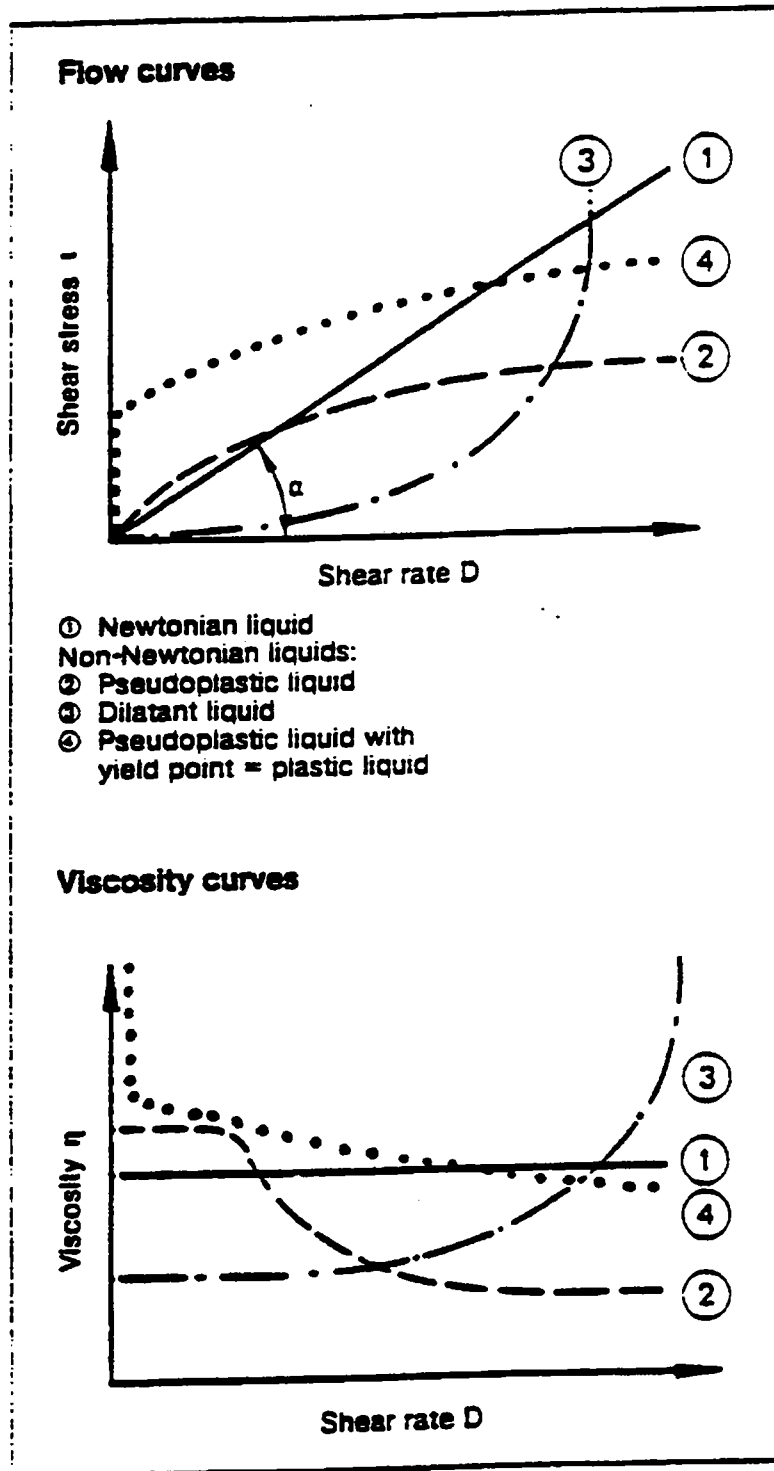
Because the flow curve for an ideal liquid is straight, the ratio of all pairs of τ and D -values belonging to this line is a constant. This means, that n is not effected by changes of shear rate. All liquids for which this statement is true are called "Newtonian".

Examples: water, mineral oils, bitumen, molasses, etc.

Non-Newtonian liquids

All other liquids not showing this simple "ideal" flow behaviour are called "non-Newtonian". They outnumber the ideal liquids by far.

Fig. 8 Non-Newtonian liquids.



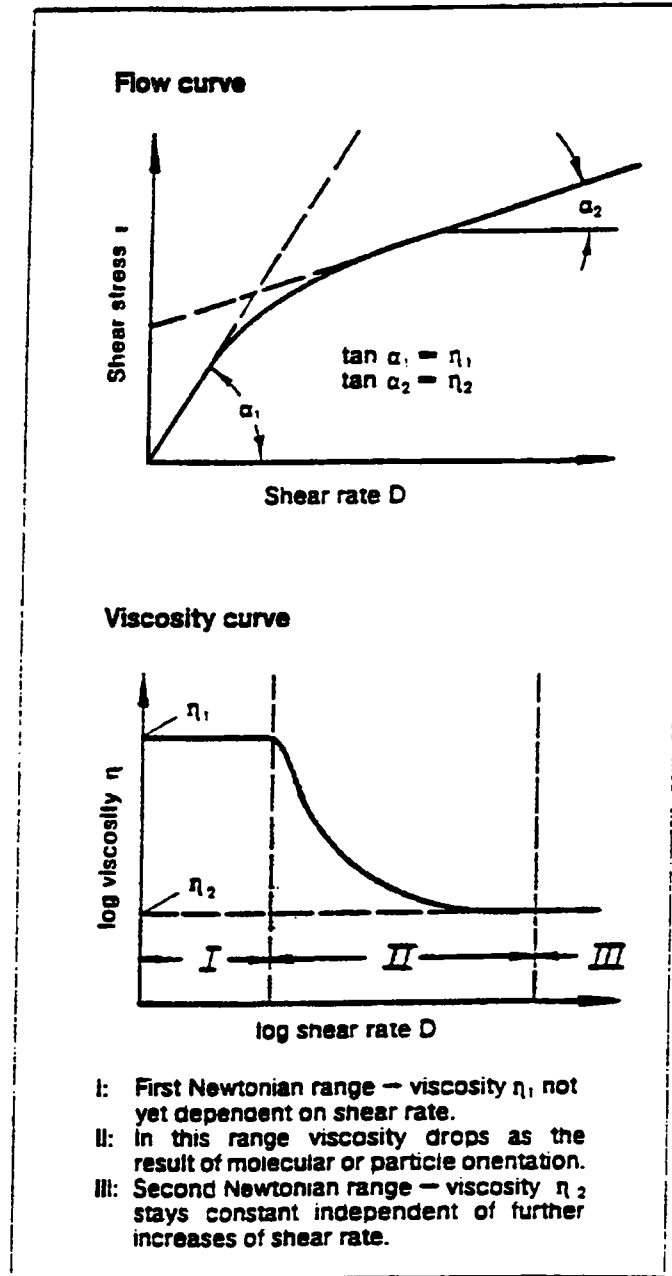
A) Pseudoplasticity

Many liquids show drastic viscosity decreases when the shear rates are increased from low to high levels.

Technically this can mean that for a given force or pressure, more material can be made to flow or the energy can be reduced to sustain a given flow rate. Materials which are thinning due to increasing shear rates are called "pseudoplastic". Substances such as emulsions, suspensions, or dispersions belong to this group.

Shear thinning of pseudoplastic liquids is not uniform over the range of very low to very high shear rates:

Fig. 9 Pseudoplasticity.



At the low shear rate range the Brownian movement of molecules keeps all molecules or particles at random in spite of initial effects of shear orientation. At very low shear rates pseudoplastic liquids behave similarly to Newtonian liquids having a defined viscosity

independent of shear rate. Then follows a shear rate change when the shear rate induced molecular or particle orientation by far exceeds the randomising effect of the Brownian movement: the viscosity drops drastically. Finally the viscosity approaches a finite level. Going to even higher shear rates cannot cause further shear thinning: The optimum of perfect orientation has already been reached. In the low and high shear rate ranges - called the first and second Newtonian ranges - the viscosity even of non-Newtonian liquids is more or less independent of shear rate.

B) Dilatancy

There is one other type of material characterised by a shear rate dependent viscosity: "dilatant" substances increase their viscosity whenever shear rates increase.

Dilatant flow behaviour is found for example in highly concentrated suspensions in which solid particles are mixed with liquids (sand slurry). The particles are densely packed and the amount of liquid added is just sufficient to fill the voids between the particles. At rest or at low coating speeds the liquid fully lubricates the particles surfaces and thus allows an easy positional change of particles when forces are applied: this suspension behaves as a liquid at low shear rates. At higher shear rates particles will wedge others apart causing a general volume increase. At this stage the liquids share of the total volume decreases. No longer being sufficient to fill all voids and to keep particle surfaces fully lubricated the slurry becomes more viscous.

Dilatancy in liquids is rare.

C) Plasticity

It describes pseudoplastic liquids which additionally feature a yield point.

Plastic liquids can be classified with good reasoning to belong to both liquids and solids. They are mostly dispersions which at rest can build up an intermolecular/interparticle network of binding forces (polar forces, van der Waals forces, etc.). These forces restrict positional change of volume elements and give the substance a solid character with an infinitely high viscosity. Forces acting from outside, if smaller than those forming the network, will deform the shape of this solid substance elastically. Only when the outside forces become so big that they can overcome the network forces - surpass the threshold shear stress calls "yield point" - does the network collapse. Volume elements can now change positions irreversibly: the solid turns into a flowing liquid. Plastic liquids have flow curves which intercept the ordinate not at the origin, but the yield point level of τ_0 .

D) Thixotropy

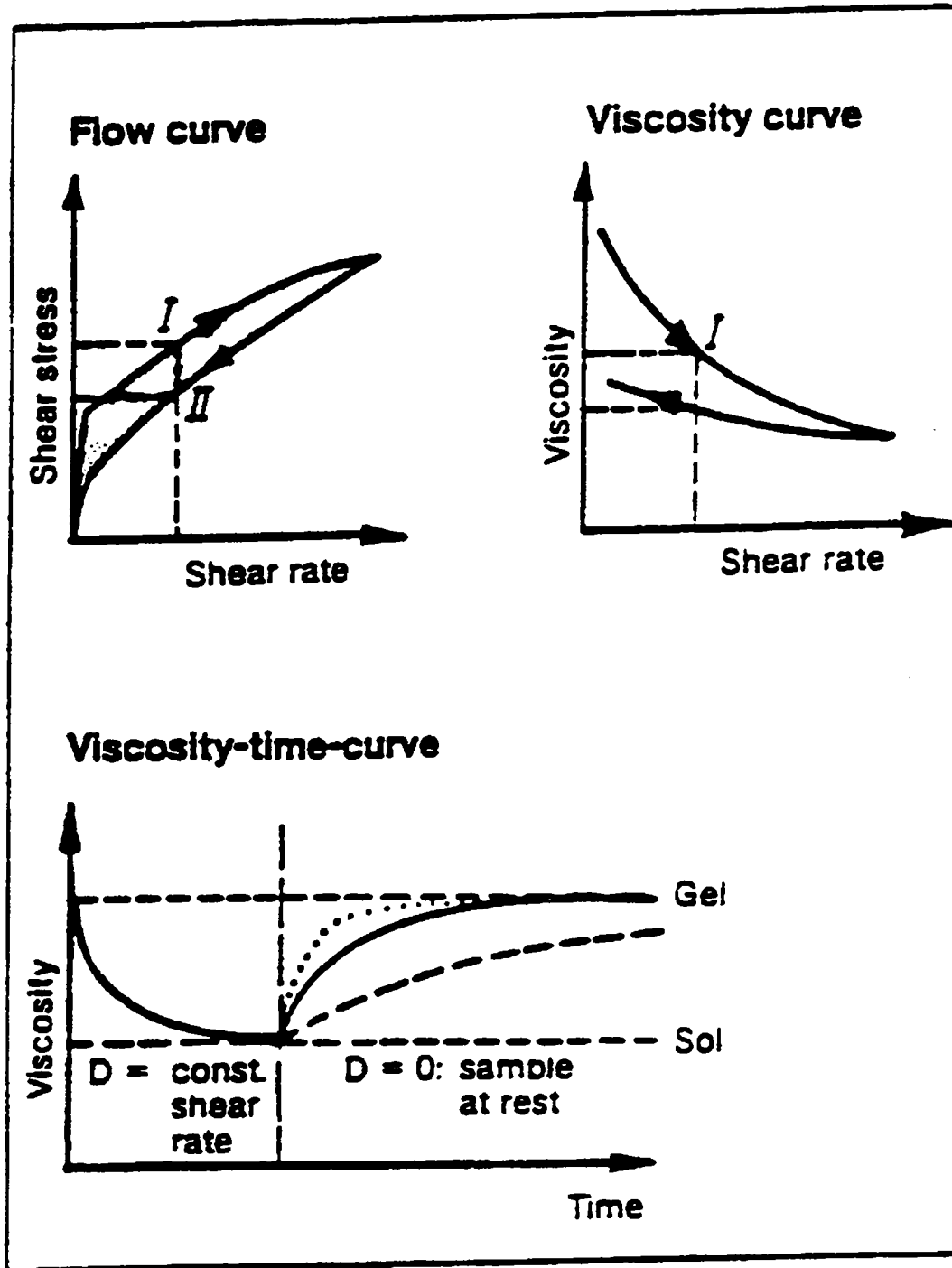
This term describes a rheological phenomenon of great industrial importance in the cement industry. It calls for some explanations in simplified terms of an otherwise often very complex molecular or particle interaction:

In pseudoplastic liquids thinning under the influence of increasing shear depended mainly on the particle/molecular orientation or alignment in the direction of flow. This orientation will again be lost just as fast as orientation came about in the first place.

Plotting a flow curve with a uniformly increasing shear rate - the "up-curve" - one will find that the "down-curve" plotted with uniformly decreasing shear rates will just be superimposed on the "up-curve".

In the flow curve the "up-curve" is no longer directly underneath the "down-curve".

Fig. 10 Thixotropy.

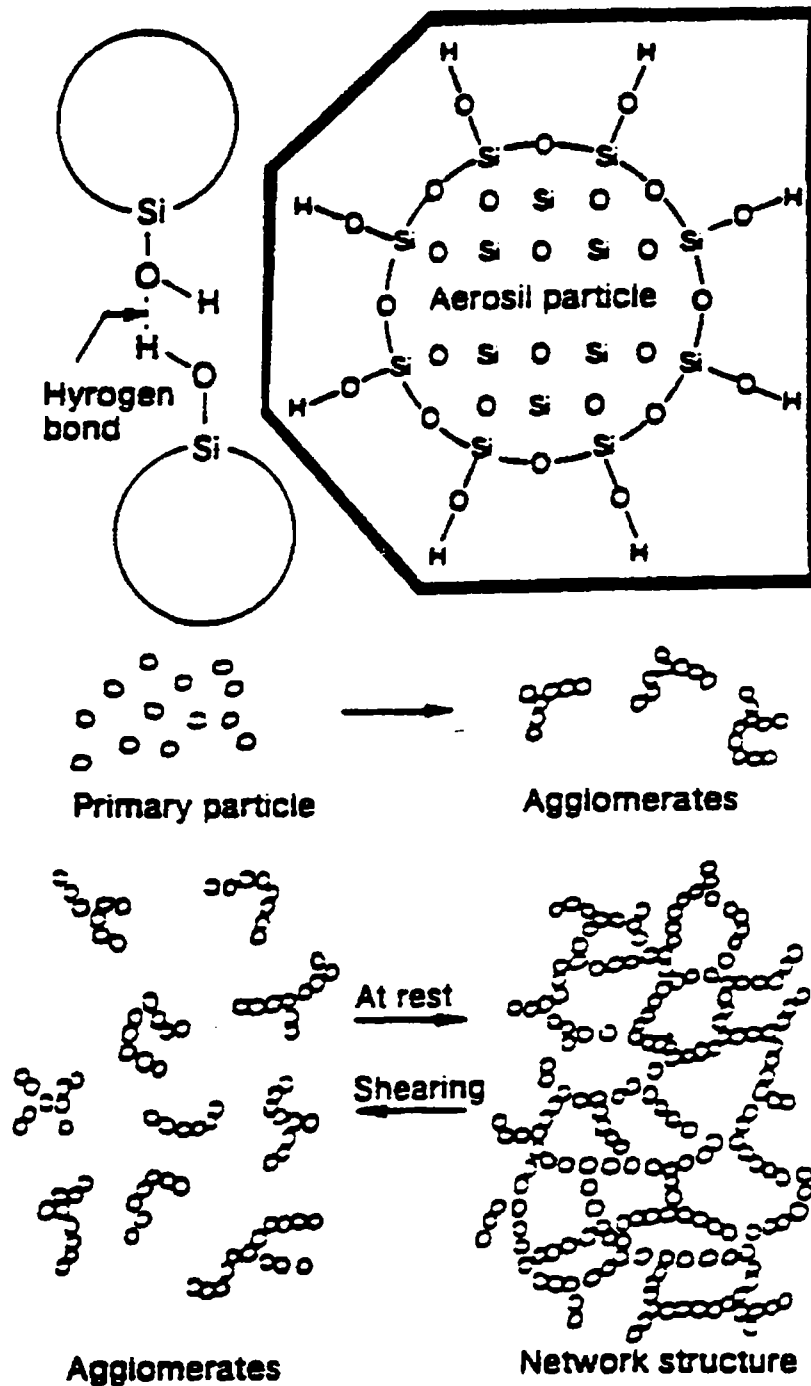


The hysteresis now encountered between these two curves surrounds an area "A" that defines the magnitude of this property called thixotropy. This area has the dimension of "energy" related to the volume of the sample sheared, which indicates that energy is required to break down the thixotropic structure.

Mechanism

It is typical for many dispersions that they not only show this potential for orientation but additionally for a particle/molecule-inter-action. This will lead to bonds creating a three-dimensional network structure which is often called a "gel". In comparison to the forces within particles or molecules, these bonds - they are often hydrogen or ionic bonds - are relatively weak: they rupture easily, when the dispersions are subjected to shear over an extended period of time.

Fig. 11 Mechanism.



When the network is disrupted the viscosity drops until it asymptotically reaches the lowest possible level for a given constant shear rate. This minimum viscosity level describes the

"sol"-status of the dispersion. A thixotropic liquid is defined by its potential to have its structure reformed, when the substance is allowed to rest for an extended period of time. The change of a gel to a sol and of a sol to a gel is reproducible any number of times.

E) Rheopexy

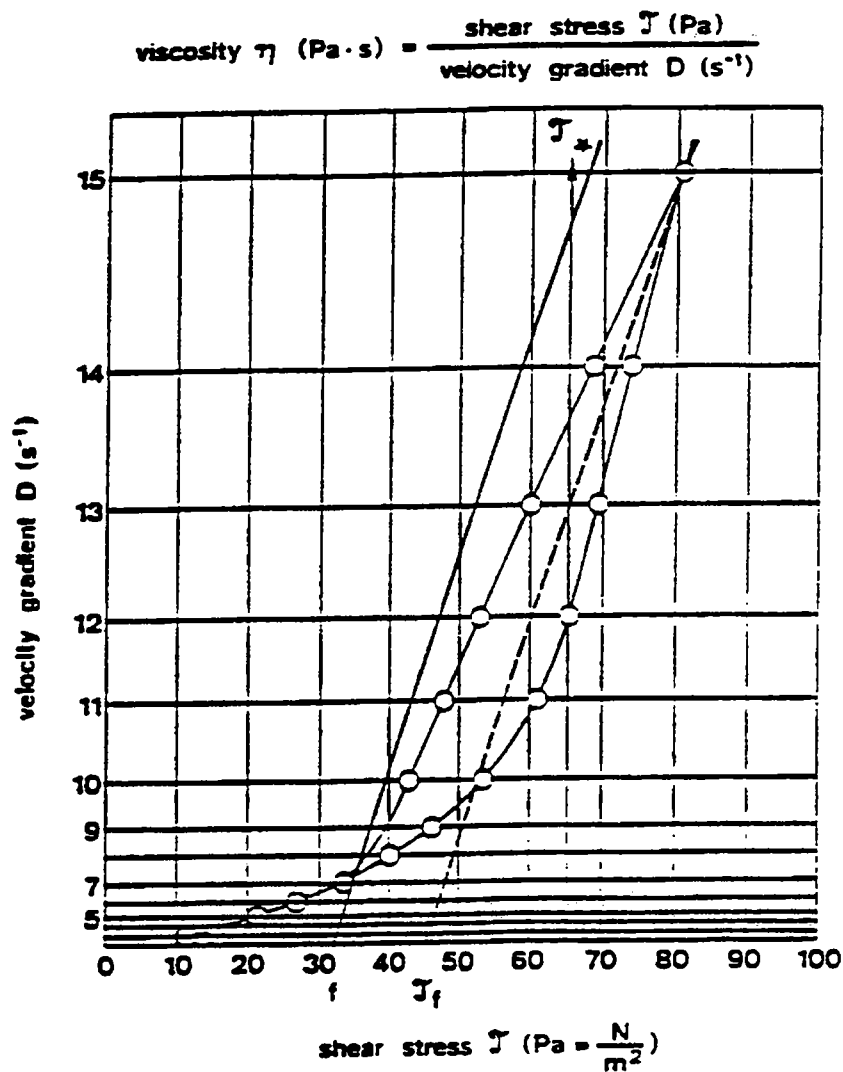
Rheopexive liquids are characterised by a viscosity increase related to the duration of shear. When these liquids are allowed to rest they will recover the original - i.e. the low - viscosity level. Rheopexy and thixotropy are opposite flow properties.

Slurry Flow Curve

A typical cement raw slurry flow curve is shown below.

This curve clearly demonstrates the plastic thixotrope characteristics of a typical cement raw slurry.

Fig. 12 **Slurry Flow Curve.**



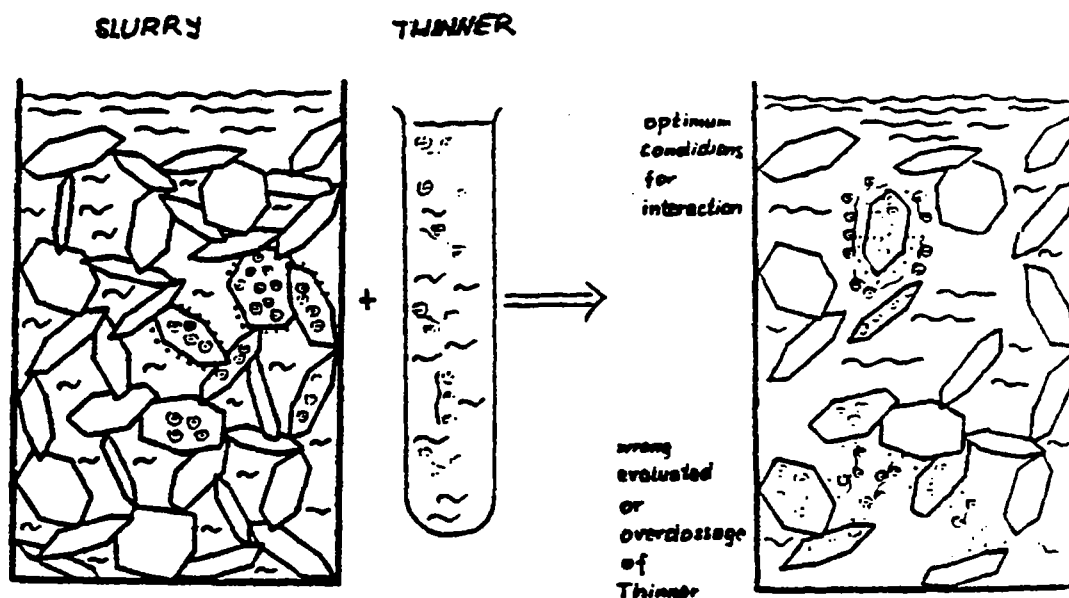
8.2 Slurry Thinners

Very small additions of thinning agents have a marked reducing effect on the water content of a slurry. However, a minimum fluidity and thus a minimum pumpability of the slurry should be maintained, in order to prevent difficulties with thickening of slurry in the chain system.

Normally, the yield values of pumpable raw slurry range between 30 and 60 Pa with a respective slurry water-content of 32 to 38%.

For a better understanding of the mechanism of slurry thinning effect, one of the many interaction models is explained:

Fig. 13 Slurry Thinners.



The slurry particles consists of small flat plates. The areas are occupied with negative electronic charge, the corners are positively charged. Stable electrostatic bridges between areas and corners reduces the flowability of the slurry .

Negatively charged thinners (e.g. polyelectrolyts) forms a protective layer around the positively charged particle corners and lowers the slurry viscosity. In case of overdosage or wrong evaluated thinner the opposite effect can occur: the polyelectrolyte forms bridges between the particles and increase the stickiness of the slurry (flocculation).

Single thinning agents

Sodium salts	Phosphates
hydroxide	sodium or potassium metaphosphate
carbonate	mono-sodium phosphate
monovinyl-sulfonate	all-sodium phosphate
carboxymethyl-cellulose	tri-sodium phosphate
chloride	sodium hexametaphosphate
oxalate	sodium pyrophosphate
fluoride	polyphosphoric acids
silicate (water glass)	

Vegetable decomposition products	Sulfite lye, lignin-sulfonate
peat and "boggy components"	sulfite lye
peat extract	sulfite alcohol slop
	sulfite spirit slop
	protein
	tanning substances (extracts)
	calcium ligno-sulfonate
	lignin-sulfonate

Surfactants with acidic groups	Organic acid salts
Polyacid salts	citrate
polysilicic acids	tartrate
polymolybdenic acids	
polyborophosphoric acids	

- ◆ Carbon dioxide
- ◆ Tensides
 - anion-active
 - non-ionogenic
 - cation-active

Combinations of thinning agents

- ◆ Phosphates + sodium or calcium salts
 - phosphate + sodium carbonate
 - phosphate + sodium hydroxide
 - phosphate + calcium hydroxide
- ◆ Water glass + soluble salts of humic or lignic acid
- ◆ Citrate + tartrate
- ◆ Carbon dioxide + sodium triphosphate (STPP)
- ◆ Triethanolamine + gallic acid

- ◆ Sulfite lye + soda

Experience with Slurry Thinning

From tests on thinning of both industrial and laboratory raw slurries, the following conclusion can be drawn :

- ◆ A large number of thinning agents produce the desired effect.
- ◆ Not every thinning agent is suited for every type of slurry.
- ◆ Under certain conditions, a combination of thinning agents added as a mixture or successively produce a better effect than one single thinning agent.
- ◆ The actual effect of a thinning agent for specific conditions cannot be predicted in advance so that tests in laboratory and in plant have to be conducted (synergism-effect, non-linearity).
- ◆ The adding quantities vary from case to case.
- ◆ The water reduction usually varies in absolute terms between 2 and 7%.
- ◆ Slurries with an initial water content between 33 and 43% have been most frequently treated with thinners.
- ◆ The mineralogical composition of a raw slurry plays an important role.
- ◆ The pH value may be a decisive factor determining the thinning effect.
- ◆ Due to local availability and for economical reasons, the most frequently used thinners are soda, water glass, STPP, sulfite lye and lignin-sulfonate.
- ◆ The fineness of a raw slurry is of little or no importance as regards the action of the thinners.
- ◆ The existing kiln systems usually require no adaptations with regard to chains and filters provided that the water content of the slurry remains above 33 - 35%. However, some plant adaptations are usually necessary, if the water content of thinned industrial raw slurries is low (30 - 33%).
- ◆ Under certain conditions, piston pumps should be installed instead of centrifugal pumps and as many bends as possible should be eliminated from the slurry piping, especially if the cement raw slurry shows rheopexic behaviour.
- ◆ For each % of water saved. 60 - 100 kJ are economised during the burning process.
- ◆ A sequential addition is important for a combination of thinners. First of all, a thinner must be added to adjust the pH and once this effect is reached, a second thinner can be added; afterwards, a third thinning agent can be used if necessary. If all of the thinners are added at the same time and place, generally the effect is not the same as with a sequential addition.

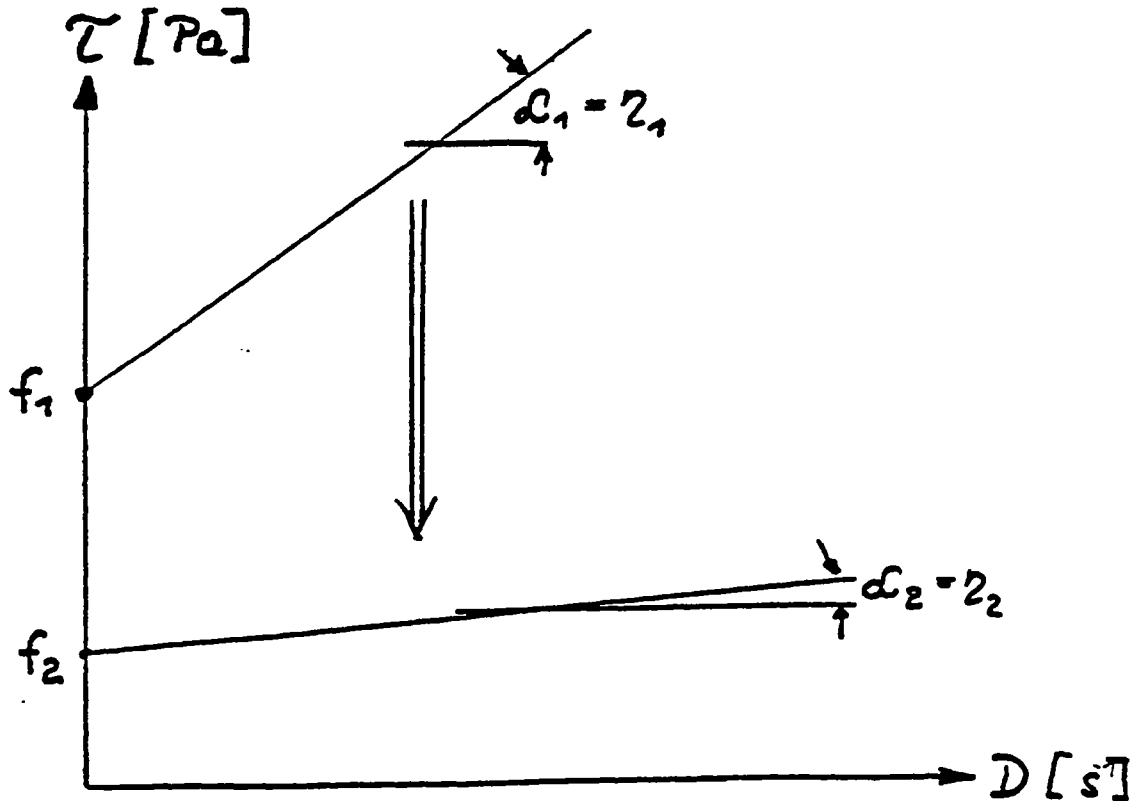
The use of a thinner should be economical, that is, the price of a thinner plays a decisive role (see also chapter "Cost Analysis). It also has to be taken into consideration that specific thinners are, or should be preferred depending on the country or location of the plant (molasses from the sugar industry, sulfite lye from the paper mills).

8.3 Viscosimetry

Laboratory methods

Target of the laboratory investigation is the reduction of the water content and/or the reduction of the yield value (f_1 to f_2) and the viscosity (α_1 to α_2). A target could also be to decrease the slurry water content and to keep yield value and viscosity constant.

Fig. 14 Laboratory methods.



As mentioned before, reduction of the water content leads to lower thermal and mechanical energy demand, reduction of yield value and viscosity to better pumpability and dewatering property (half wet process).

For the purpose of optimizing the slurry viscosity it is indicated to make trials with different thinner admixtures, concentrations, retention time and temperature levels in the laboratory.

Recent developed method of statistical experimental planning helps to minimise laboratory work drastically.

The main 6 influencing parameters to investigate are
- water content of slurry
- thinner quality
- thinner concentration
- quality of raw material (depending on clinker quality)
- retention time
- slurry temperature

The target is to find out a quantitative relationship between viscosity and above mentioned parameters. The assumption of 3 experimental level of above 6 influencing parameters means

36 = 729 experiments

This number is, of course, unacceptably high. By application of statistic methods 45 relevant experiments can be evaluated.

After the experiments are done, the quantitative relationship is generated by a regression function. This regression function leads to the optimum parameter constellation and can also be implemented into a PLC ("Model based Process Control").

Rotational Viscosimeter

The instrument of the laboratory investigation is the so-called "Rotational Viscosimeter". State of the art is the automated unit.

The principle of rotational viscometers with coaxial cylinder sensor systems and with cone-and-plate sensor systems allows the design of excellent and versatile absolute viscometers. The range of rotational viscometers on the world market varies widely in sophistication and in price. The rheological criteria mentioned before are being used to grade types of instruments and explain design features and resulting areas of application.

One might imagine that the coaxial cylinder sensor systems for rotational viscometers result from bending both flat plates of the Newton's parallel-plate-model into an inner and outer cylinder. A liquid sample filling the annular gap between the two cylinders can be exposed to shear. Conditions will lead to laminar flow and allow a mathematical treatment of the problem.

Two alternatives are open to turn the above geometry into an absolute viscometer:

a) Preselect τ : look for D

The inner or the outer cylinder is subjected to a defined shear stress or a defined torque while the other cylinder is held at rest. One can now measure the rate of rotation or shear rate resulting.

b) Preselect D: look for τ

c) The inner or the outer cylinder rotates at a defined rotational speed while the other cylinder is held at rest. One can now measure the resulting shear stress or torque. This is the most common design for rotational viscometers.

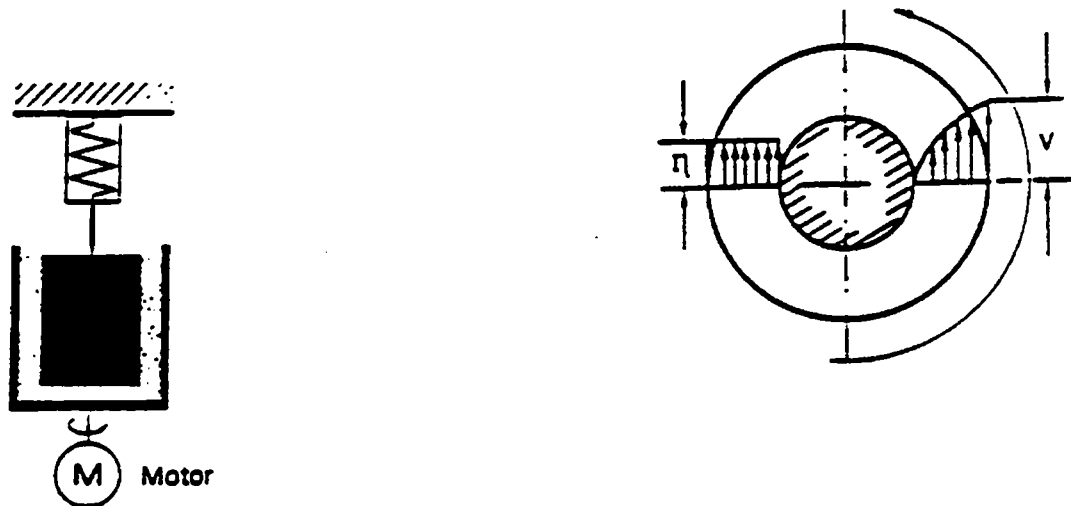
d) This type of viscometer can come in two versions:

- * Searle system

The inner cylinder - often called the "rotor" - rotates at a defined speed. The outer cylinder - often called the "cup" - is held at rest. The rotating inner cylinder forces the slurry in the annular gap to flow. The resistance of the slurry being sheared between the stationary and rotating boundaries results in a viscosity related torque working on the inner cylinder which counteracts the torque provided by the drive motor. A torque sensing element - normally a spring that twists as the result of the torque - is placed between the drive motor and the shaft of the inner cylinder. The twist of the torque spring is a direct measure of the viscosity of the slurry tested.

Most viscometer models made world-wide are Searle types. One reason for this tendency is that the good temperature control required for viscosity measurements is more easily accomplished when the outer cylinder does not rotate. Searle type viscometers are limited when low viscous samples have to be tested at high rotor speeds. Centrifugal forces affecting the liquid can turn laminar flow to non-laminar flow and eventually to a fully developed turbulence.

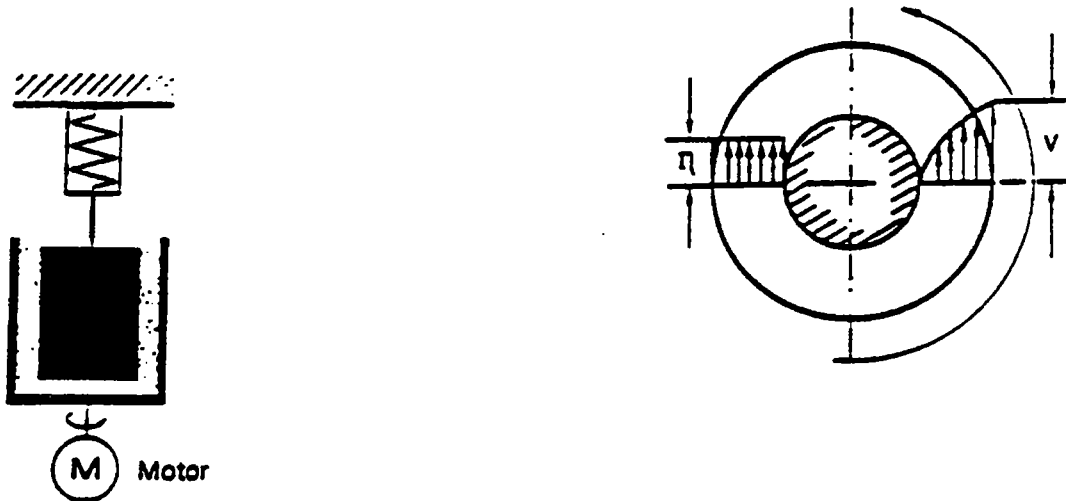
Fig. 15 Searle System.



* Couette system

The outer cylinder rotates at a defined speed. It forces the slurry sample in the annular gap to flow. The resistance of the slurry being sheared, transmits a viscosity related torque onto the inner cylinder, which would induce it also to rotate. This torque is measured by determining just what counteracting torque is required to hold the inner cylinder at stand still. Couette type viscometers are more stable with respect to centrifugal forces.

Fig. 16 Couette System.



9. PRODUCTION COST ANALYSIS

Basic is to describe the process in mathematical "Cost Analysis" is to find out the minimum of all specific costs as a function of the raw slurry water content (viscosity).

Approach

- 1) In a first step a qualitative technical relationship has to be established. This relationship describes the demand on thermal and mechanical energy in function of the water content (viscosity) of the raw slurry.
- 2) The technical functions are to be evaluated with the specific factor prices, resulting in "Partial Variable Cost Functions".
- 3) The addition of the "Partial Variable Cost Functions" gives the a Total Variable Cost Function".
- 4) The minimum of the "Total Variable Cost Function" shows the optimum water content (viscosity).
- 5) To evaluate new investments it is possible to combine the "Total Variable Cost Function" with a II Fixed Cost Function" to a "Total Cost Function" .

9.1 Technical functions

Several important aspects of slurry preparation are seen in a wet/semi-wet plant. Some of them are:

- ◆ Pumping energy demand
- ◆ Waste gas ventilation demand
- ◆ Pump evaluation
- ◆ Filtration energy demand
- ◆ Thermal energy (enthalpy) demand

As examples short, simplified overviews are given. Basic consideration is to show the specific energy demands as a function of the raw slurry water content.

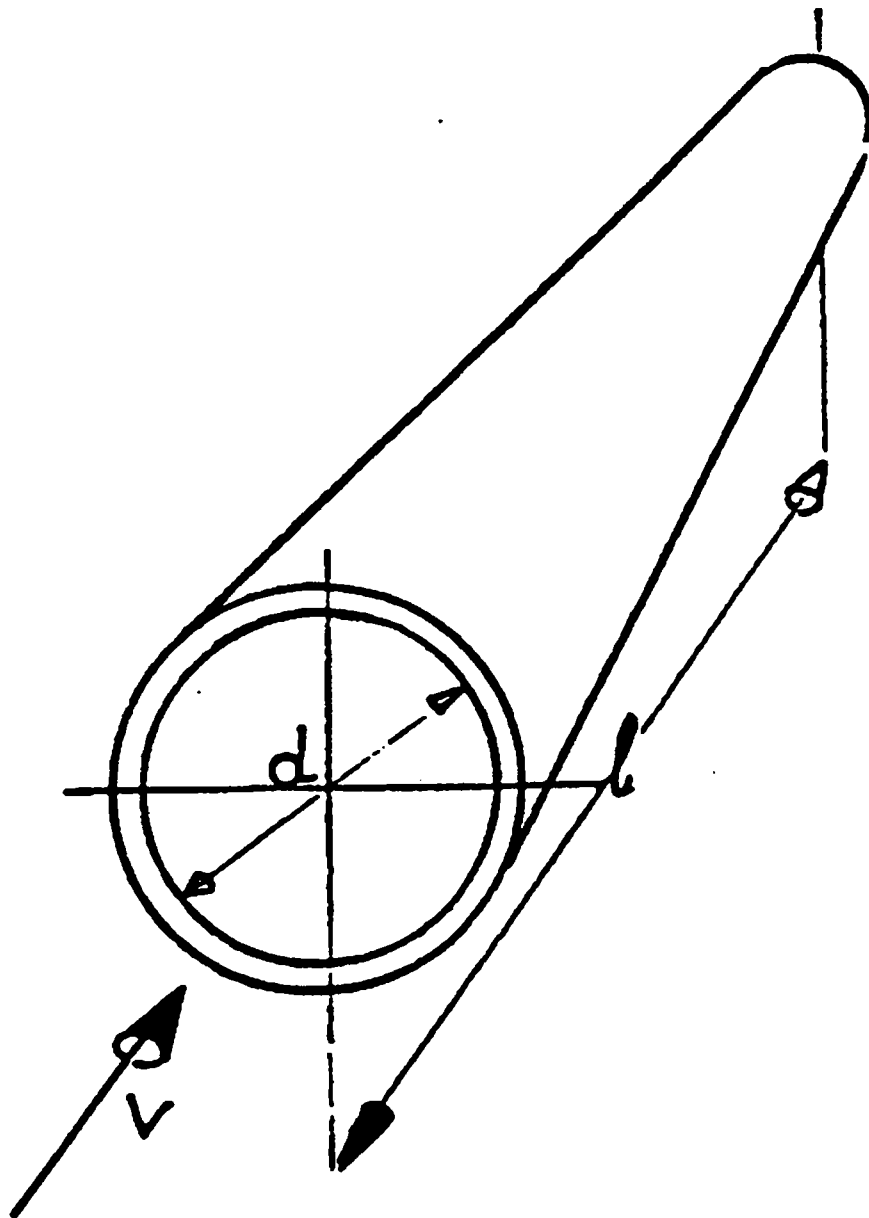
9.1.1 Piping system

There are several parameters known with regard to flow resistivity of a piping system:

- ◆ length of piping
- ◆ diameter of piping (flow-velocity)
- ◆ inner surface quality of piping
- ◆ amount and design quality of bends, valves, fittings, ducts

In a simplified form the approach to achieve the flow resistivity function is shown on a simple pipe piece:

Fig. 17 Simple pipe.

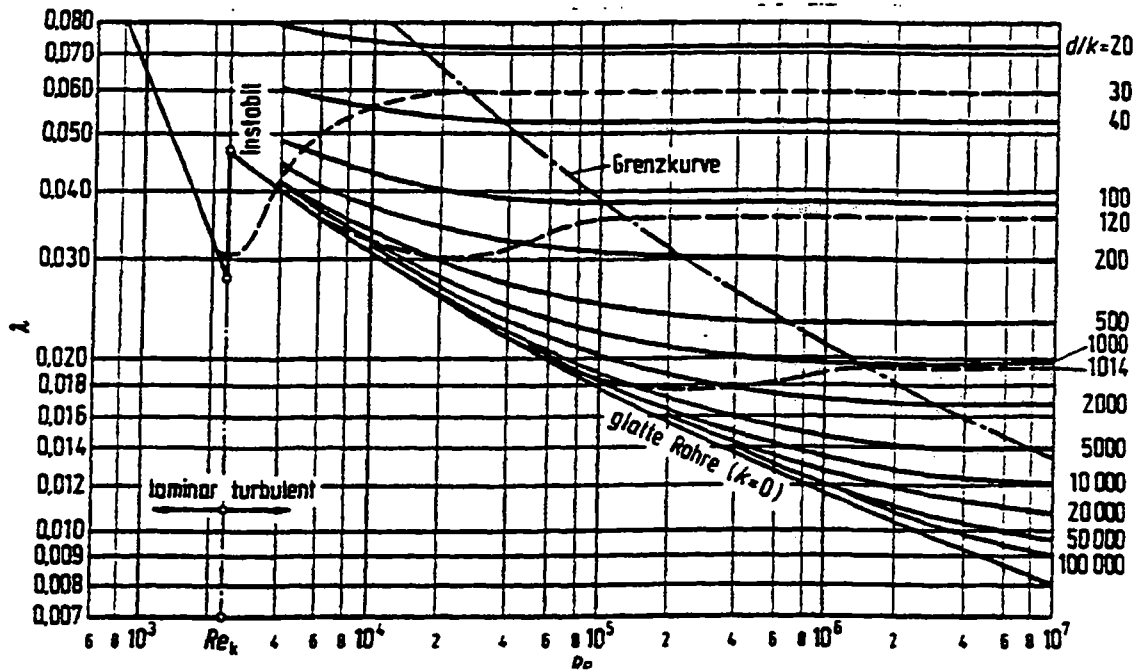


First step is to outnumber the "Reynolds Number" Re

$$Re = \frac{v \times d \times \delta}{\eta}$$

Second step is to evaluate the friction number λ as a function of Re a quality of the pipe surface (d/k). The following diagram also shows the interface between laminar and turbulent flow.

Fig. 18 Laminar and Turbulent Flow.



In the laminar flow zone no relation between pipe surface quality and resistivity number exists, whereas the influence in the turbulent flow zone increase drastically.

In the laminar flow zone the simplified approach to evaluate the flow resistivity number is possible by applying the "Hagen Poiseulle's law":

$$\lambda = \frac{64}{Re}$$

With the flow resistivity number it is easily possible to compute the pressure drop of a simplified piping system as follows:

$$\text{Pressure drop} = \lambda \times \frac{1}{d} \times \delta \times \frac{v^2}{2g}$$

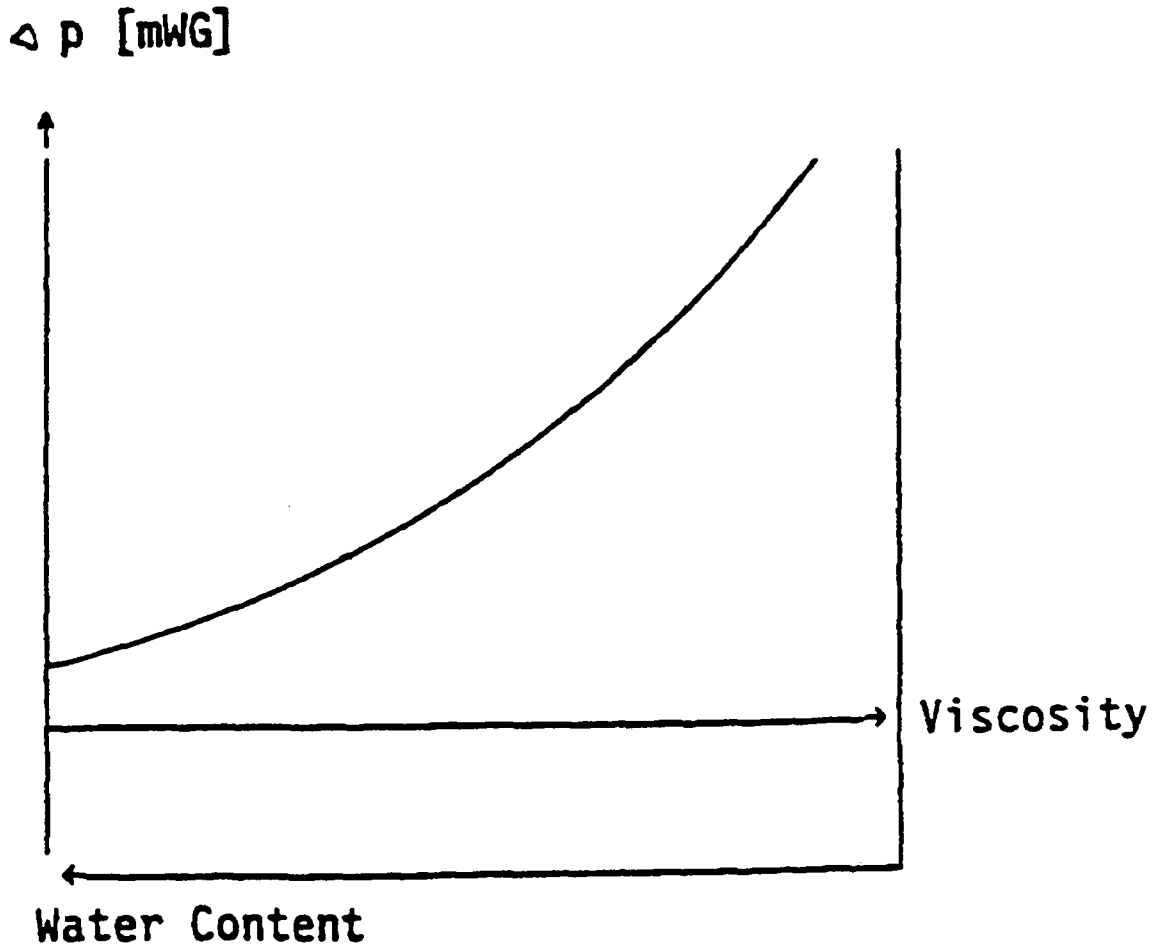
Pressure drops results from flow resistivities, elevation differences (geodatical) and velocity difference between input and output of the piping system.

Total pressure drop

$$\sum \Delta p = \sum \lambda \times \frac{L}{d} \times \delta \times \frac{V^2}{2g} + \sum \xi \times \frac{V^2}{2g} + \frac{V_{(ou)} - V_{(IN)}}{2g} \times \delta$$

With this relationship the function of "Pressure drop" depending on slurry viscosity (water content) can be given quantitatively:

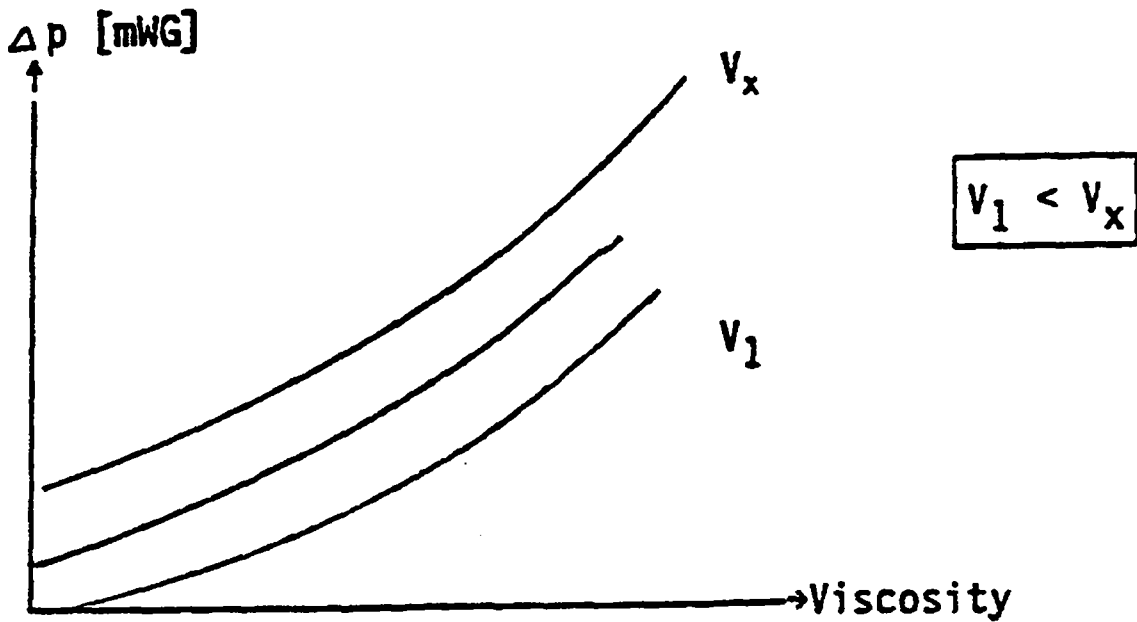
Fig. 19 Pressure Drop.



9.1.2 Pump evaluation

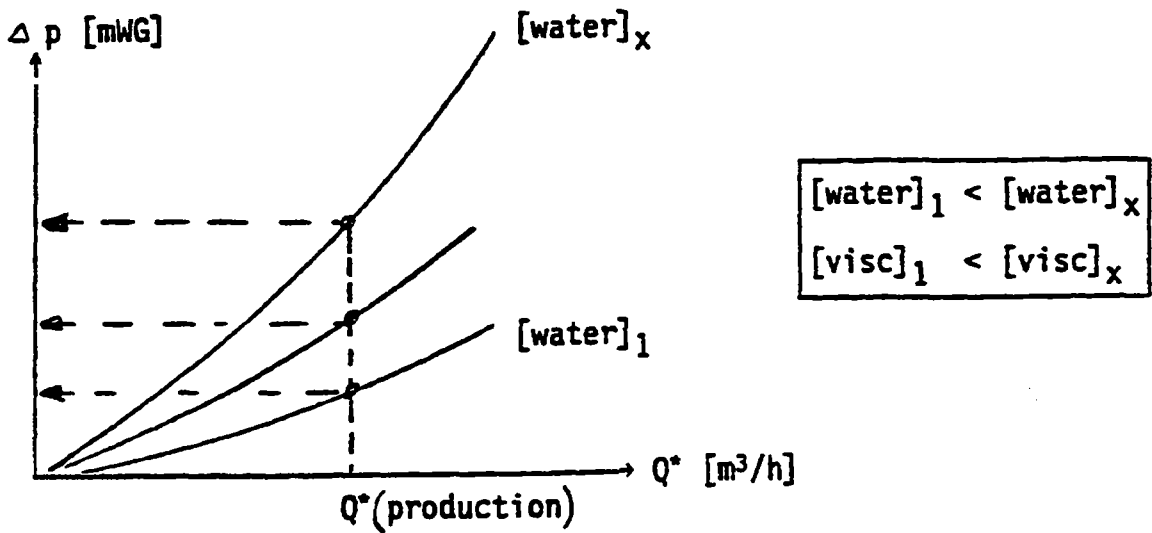
As shown before, the pressure drop of a piping system depends on viscosity (η) and on velocity (v):

Fig. 20 Viscosity against Velocity.



Viscosity and Velocity depends on water content of slurry, so the following relation can be formed:

Fig. 21 Water content.



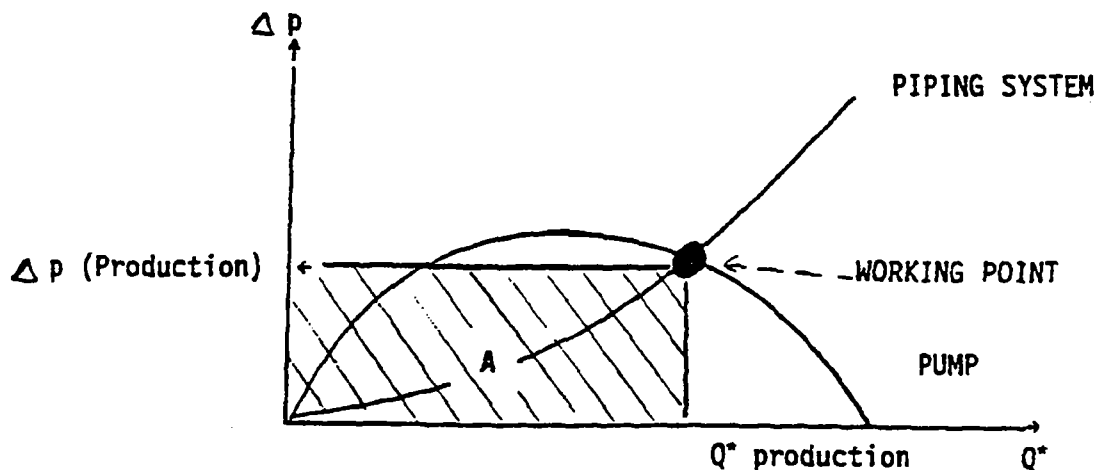
Curve parameter is Water Content of Cement Raw Slurry

Pump power demand = $\Delta p \times Q^*$ (Production)
--

Optimisation

Qualitatively the correlation before show the influence of Water Content Viscosity to the Pump power demand. To evaluate the optimum pump, the pump characteristic in relation to the efficiency must be known:

Fig. 22 Optimisation.



Q^* production, pump efficiency and pump characteristic dictates the pump evaluation and the power demand. The area "A" represents the pumping power demand, the value has to be minimised.

This consideration leads to a complex, multivariable optimisation. It is worthwhile doing it in face of the great saving potential of investment cost and mechanical energy.

9.1.3 Filtration

Filtration is defined as a "solid - liquid - separation - technique", i.e. separation of a cement raw slurry into a liquid phase (the filtrate) and a solid phase (filter cake) with the aid of a filter which can only be penetrated by liquids. This process is applied in the so called "semi-wet process".

Kozeny - Carman's law

$$Q^* = \frac{1}{\eta} \times k \times \frac{\Delta p}{S^2} \times \frac{E^3}{(1-E)^2} \times \frac{A}{e}$$

k System constant

A Filtration Area

S Specific surface of solids

E Porosity

The equation demonstrates that - in order to achieve a short filtration time - the working pressure (P) should be high (up to 25 bar under industrial conditions), the total filter area large (up to 100 plates per filter press), porosity as high as possible, but the viscosity low.

9.1.4 Thermal Energy Demand

The main reason to decrease the raw slurry water content is to reduce the thermal energy demand of the drying phase prior the clinker burning in the wet kiln. The simple function show the linear relationship between water content and thermal evaporation enthalpy:

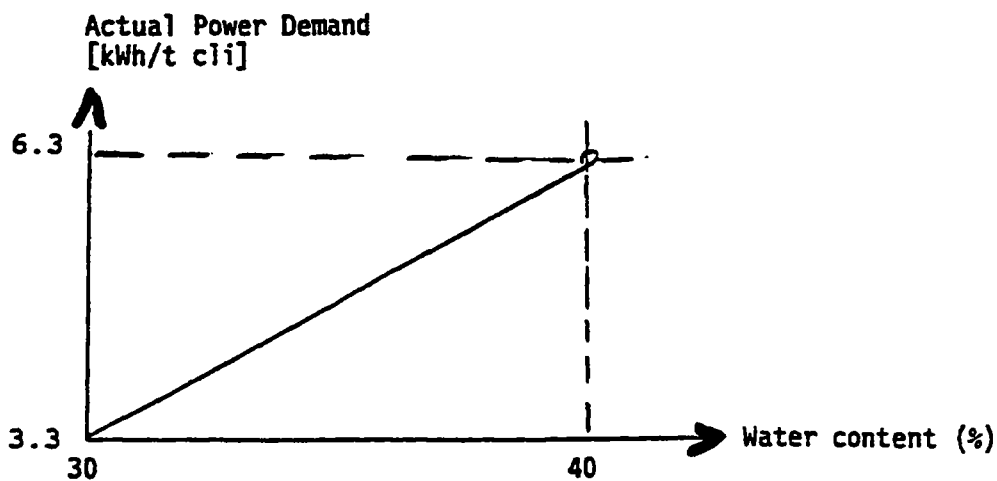
$$H = \frac{[H_2O] \times 10}{1 - [H_2O]} \times F_{cli} \times 2450 \text{ [kJ / kg cli]}$$

H Specific Evaporation Enthalpy
 [H₂O] Water Content of Slurry (%)
 f_{cli} Clinker Conversion Factor

9.1.5 Exhaust Fan Energy

The simplified relationship between demand on mechanical exhaust fan energy and water content of raw slurry is shown below. Pressure drop through kiln varies between 100 - 150 mm WG, the kiln is coal fired (25'000 kJ/kg). Fan efficiency = 0.8, no oxygen content of waste gas.

Fig. 23 Exhaust Fan Energy.



9.2 Optimisation

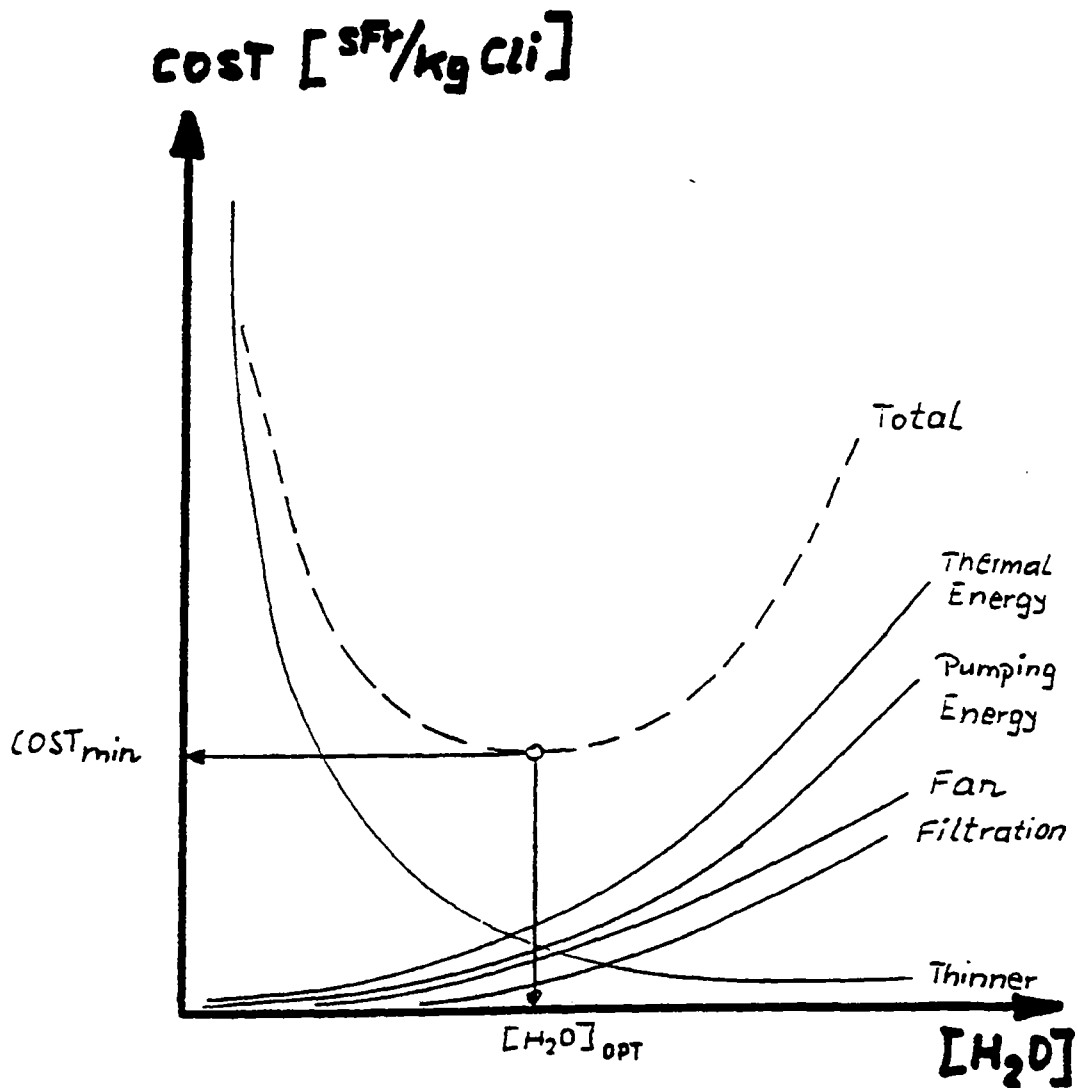
The given technical functions are now to be evaluated by the specific prices in order to get "Cost-functions".

This means the multiplication of specific demands with the specific prices of

- ◆ Pumping energy
- ◆ Thermal energy
- ◆ Exhaust fan energy
- ◆ Filtration
- ◆ Thinners
- ◆ etc.

Qualitatively the "Cost-Function" is shown in relation to the water content of the slurry [H₂O] %.

Fig. 24 Cost Function.



The addition of all specific cost functions leads to the "Total Cost Function". This function has the minimum point (optimum operational point) of course on the lowest operation cost. On this point of the function the economical best water content of the slurry is to find.

